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Detection and Characterization of Flaws in Sprayed on Foam Insulation with Pulsed Terahertz Frequency Electromagnetic Waves

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The detection and repair of flaws such as voids and delaminations in the sprayed on foam insulation of the external tank reduces the probability of foam debris during shuttle ascent. The low density of sprayed on foam insulation along with it other physical properties makes detection of flaws difficult with conventional techniques. An emerging technology that has application for quantitative evaluation of flaws in the foam is pulsed electromagnetic waves at terahertz frequencies. The short wavelengths of these terahertz pulses make them ideal for imaging flaws in the foam. This paper examines the application of terahertz pulses for flaw detection in foam characteristic of the foam insulation of the external tank. Of particular interest is the detection of voids and delaminations, encapsulated in the foam or at the interface between the foam and a metal backing. The technique is shown to be capable of imaging small voids and delaminations through as much as 20 cm of foam. Methods for reducing the temporal responses of the terahertz pulses to improve flaw detection and yield quantitative characterizations of the size and location of the flaws are discussed.

Nomenclature

α	=	terahertz attenuation
c	=	velocity of light in a vacuum
n	=	index of refraction
m	=	ratio of the index of refraction of two materials at an interface
v_a	=	terahertz velocity in air
v_f	=	terahertz velocity in foam
d	=	void thickness
l	=	thickness of air gap
ω	=	angular frequency
k_a	=	wave number for electromagnetic propagation in air (ω/v_a)
k_a	=	wave number for electromagnetic propagation in foam (ω/v_f)
R	=	normal incidence reflection coefficient
T	=	normal incidence transmission coefficient

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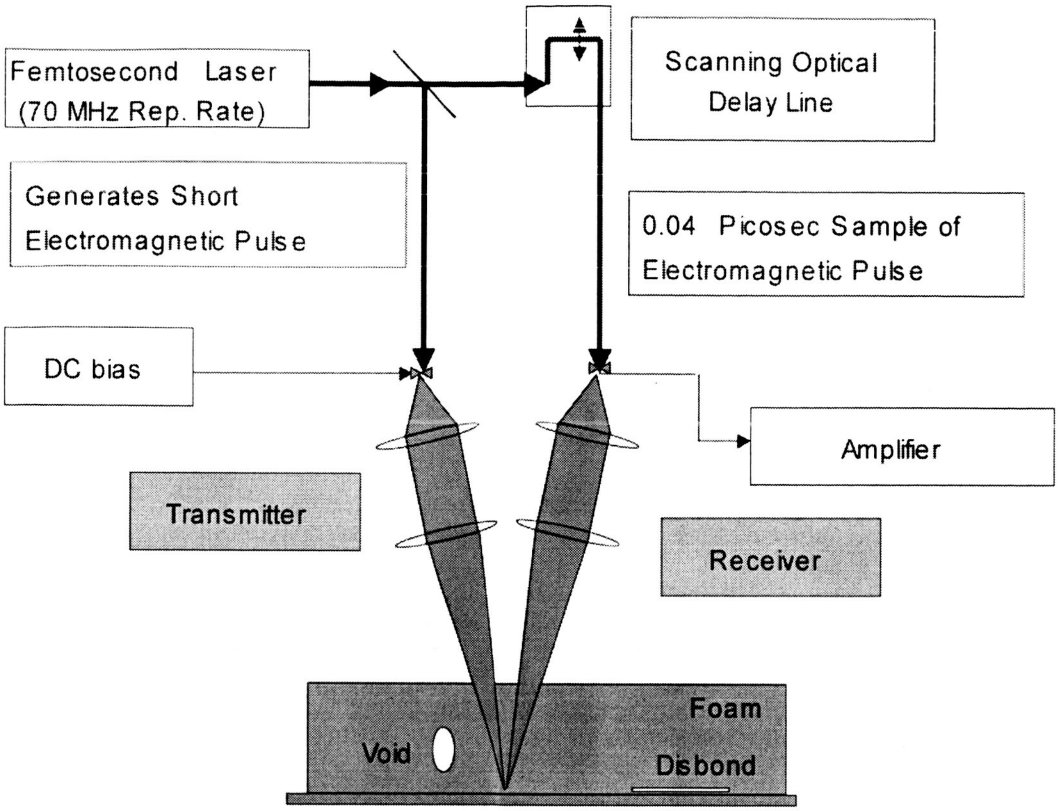


Figure 1. Schematic of pulsed terahertz measurement system.

I. Introduction

To assist in reducing foam debris from the external tank during shuttle assent, several techniques were assess for detection of subsurface flaws in the external tank sprayed on foam insulation (SOFI). The particular flaws of interest were subsurface voids and delaminations in the foam. Nondestructively detecting flaws with a single sided technique is difficult since the foam is effectively a collection of small air filled bubbles with thin polymer membranes. The resulting material is a thermal and electrical insulator with an extremely high ultrasonic attenuation. These properties make it unfeasible to inspect the foam with conventional techniques such as eddy current, ultrasonics and thermography. While conventional radiography is a viable technique when there is access to both sides of the component, the requirement for a single sided technique eliminates it as a viable inspection technique.

Two techniques were identified as viable single sided techniques. One of the techniques is backscattered x-ray, which sends a small pencil beam of x-rays into the foam and measures the x-rays scattered by the foam. The presence of a void results in a volume from which there are no backscattered x-rays, therefore a reduction in the intensity of measured x-rays. A second technique is propagating a short focused terahertz frequency electromagnetic pulse into the foam and measuring the reflection of the pulse off the metal substrate. The velocity and attenuation differences between the foam and entrapped air (voids or delaminations), enable the detection of these flaws in the foam. This paper discusses the viability of the terahertz technique for detecting flaws in foam insulation and signal processing techniques for improving the detectability of these flaws.

II. Pulsed Terahertz Electromagnetic Response Measurement Technique

Pulsed terahertz measurements are a relatively new technique, made possible partially by the development of femtosecond lasers.[1-7] A technique for generating and detecting pulsed terahertz radiation is shown in figure 1. A single light pulse from a femtosecond Ti:S laser triggers the generation and detection of terahertz radiation. The laser beam is split and part of the beam is focused on a specially grown GaAs crystal, rapidly exciting electrons into the conduction band, resulting in the shorting a small biased gap to produce a short burst of terahertz radiation. The terahertz radiation is focused and transmitted into the material or structure of interest. The radiation that is reflected from discontinuities in the index of refraction can be refocused to strike a second GaAs crystal that acts as the receiver. A second part of the same femtosecond laser pulse used for generation is focused on the receiver crystal. The femtosecond laser pulse gates on the receiver, generating a transient electrical pulse that is proportional to the terahertz radiation that is present at the receiver at that moment in time. By controlling the length of the path of the receiver beam with a scanning optical delay line, the receiver can be sampled at controlled time steps to create a time record that reproduces the received terahertz signal. The repetition frequency of the femtosecond laser is approximately 80 MHz, therefore the time require to construct a complete time record typically is limited by the speed of a scanning optical delay line and the required signal to noise. An additional feature of the system is the transmitter and receiver modules are optically fiber-coupled and environmentally sealed. This has several advantages for application of the system in a field setting. First, the fiber optics connections eliminate laser safety issues. This system also enables the fabrication of small transmitters and receivers that are freely positionable, simplifying remote scanning. For a more detailed discussion of the system refer to the paper by Zimdars et. al.[8]

To measure the spatial variations in the foam characteristics and image flaws, the transmitter and receiver are combined in a single unit (transceiver) and mounted on scanning bridge than enabled translation over a specimen. The transceiver was translated in a plane over the specimen of interested in 0.254 cm steps to capture the terahertz response of the specimen as a function of position. The time series responses were recorded and stored on a computer for later analysis.

III. Electromagnetic Properties of Sprayed on Foam Insulation at Terahertz Frequencies

The difference in the terahertz response of the foam and air fill flaws in the foam depends on the electromagnetic properties of the foam. The velocity and attenuation of the foam depends on the density of the foam and the dielectric properties of the polymer. The properties of the foam, therefore tends to vary from specimen to specimen. The terahertz phase velocity of the foam is typically measured to be from 0.96 to 0.98 c, where c is the velocity of light in a vacuum. This gives a range of index of refractions (n) for the foam of 1.02 to 1.04.

Important characteristics of the foam for detection of the discontinuities between the foam and air trapped in the foam in the form of voids or delaminations are the reflections and transmission coefficient at the interface between the air and the foam. For a normally incidence terahertz pulse, the reflection coefficient for two media is given as

$$R = \frac{(1-m)}{(1+m)} \qquad (1),$$

where m is the ratio of the first material's index of refraction to the second material's index of refraction. For a foam to air interface, this gives a reflection coefficients of -0.01 and -0.02 for foam with indexes of refraction of 1.02 and 1.04 respectively, where the negative sign indicates the reflection is inverted relative to the incident pulse. The normal incidence reflection from air foam interfaces is very small relative to reflection from the metal substrate, which has a reflection coefficient of approximately 1. Reflections from the foam air substrates therefore must be significantly separated in time from the metal substrate reflection to be clearly visible.

The normal incidence transmission coefficient (T) is given by

$$T = \frac{2}{(1+m)} \qquad (2).$$

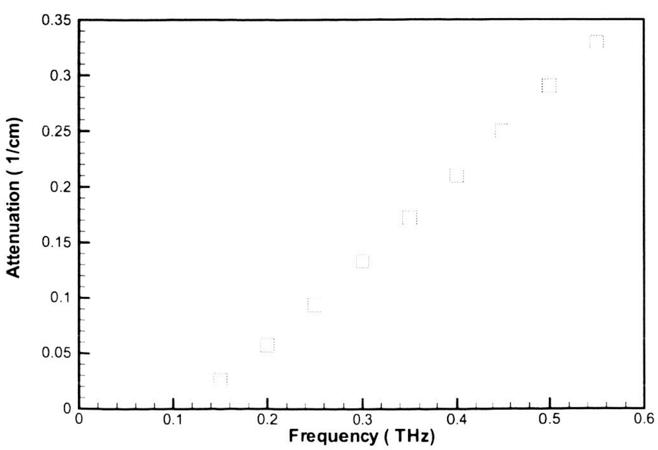


Figure 2. Attenuation as function of frequency.

For the foam to air interfaces, the transmission coefficients for normal incidence are 0.99 and 0.98 for indexes of refraction of 1.02 and 1.04 respectively, indicating there is little drop in amplitude as the wave passes through the interface.

A second important characteristic of the foam is the attenuation (α) of the foam. For the foam, the attenuation has a strong frequency dependence at terahertz frequencies. At 0.1 THz and below the attenuation is relatively small, with limited reduction in electromagnetic amplitude for foam thicknesses up to 40 cm. In comparison, at 0.5 THz, the amplitude of the electromagnetic wave is almost completely extinguished after 10 cm (reduction of more than 0.95). Figure 2 gives estimated attenuation as a function of frequency. This estimate is based on pulse measurements on different thicknesses of foam and a determination of the frequency dependency base on the variation as a function of thickness of the amplitude of the Morlet wavelet transform of the signal.

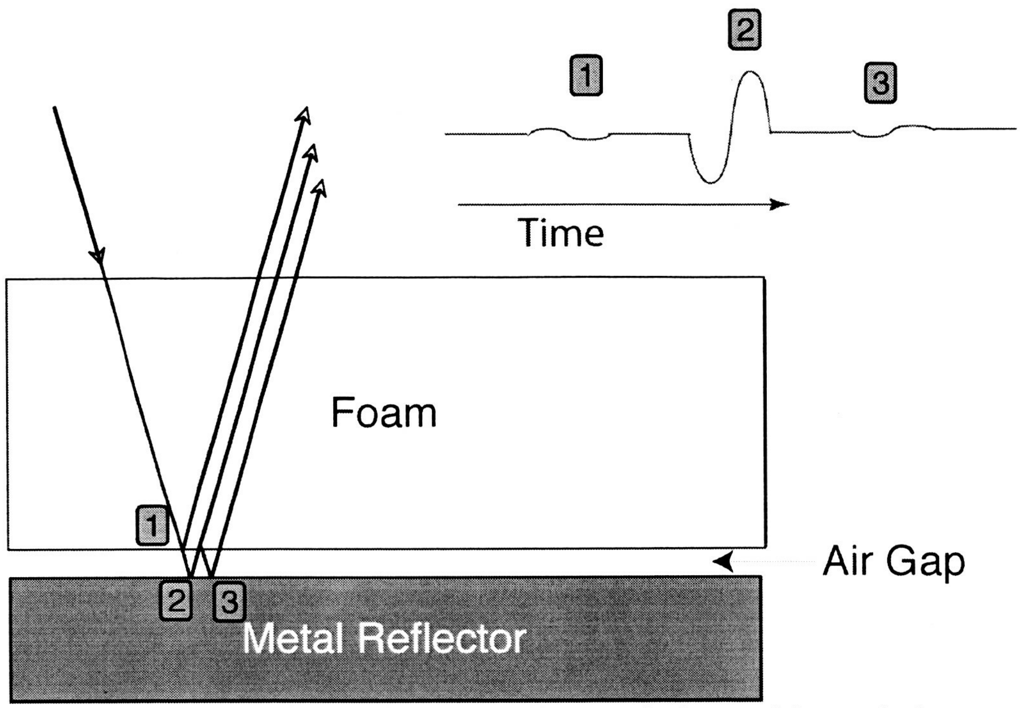


Figure 3. First three reflections from an air gap located between the foam and the metal substrate.

IV. Detection of Disbonds at the Foam-Metal Interface

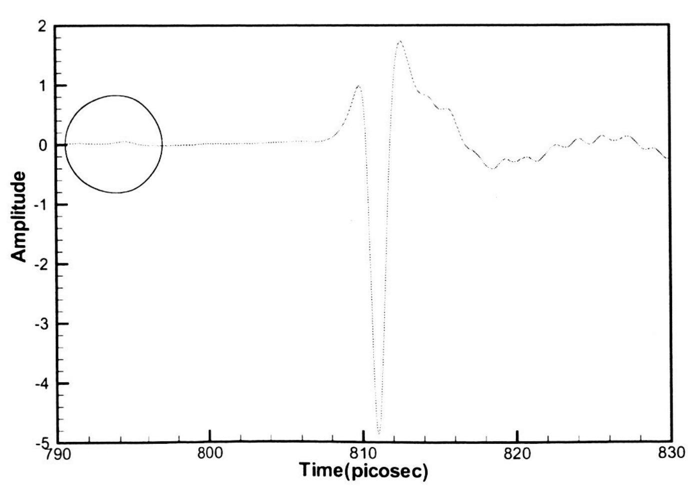


Figure 4. Measured response from air gap between foam and metal substrate. The reflection from the foam-air interface is circled.

Detection of disbonds at the foam-metal interface is only possible to date if an air gap exists between the foam and the metal substrate. Figure 3 gives the expected response if a small air gap exists between the foam and the metal. The figure shows the first three reflections expected from the air gap. As mentioned in Section 3, the reflection coefficient is on the order of -0.01 to -0.02 for the foam air interface. Subsequent reflections from the air gap would be down by another factor of 0.02, therefore even more difficult to detected. For normal incidence, the separation between echoes 1 and 2 is twice the transient time of light in the air gap or 2 l/c, where l is the width of the air gap.

The measured response for a fixed air gap is shown in figure 4. The reflection from the foam-air interface is circled in the figure. As expected the reflection from the foam-air interface is approximately 1% the amplitude of the reflection from the air metal interface at the backside of the air gap. To enhance the visualization of the foam-air interface reflections, the large reflection from the air metal interface was computationally remove. The resulting wave forms for different gap widths varying from pressed contact between the foam and metal to an air gap of 5.71 mm is shown in figure 5.

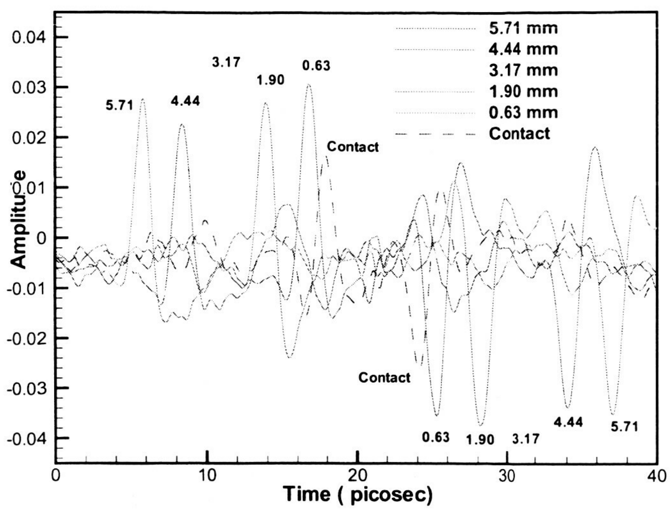
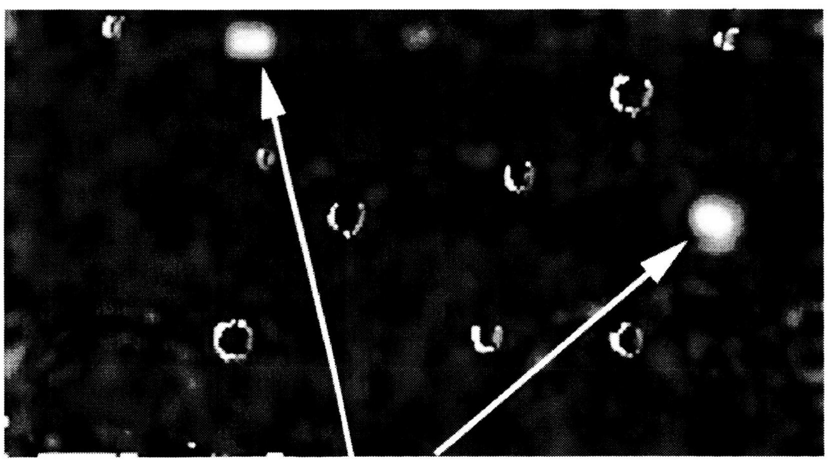


Figure 5. Response from air gap between foam and metal with the first reflection from the air-metal interface removed. Each waveform is labeled with the width of the air gap.

As can be seen from the figure, both the first and third reflections as delineated in figure 3 are visible when the reflection from the air-metal interface is remove. The separation of these two reflections as expected is linearly dependent on the width of the gap. The third reflection has approximately the same amplitude as the first reflection, however is inverted, since the reflection coefficient of the foam to air interface is negative (transition from higher to lower index of refraction) and the third reflection is proportion to the reflections from the air-metal interface and air-foam interface, which are both positive.



Disbonds

Figure 6. Amplitude of the reflection from foam-air interface of intentionally inserted disbond.

In applications to date, removal the reflections from the air-metal interface from the total response has not been performed for scans of the foam bonded to a metal subtract. However, it has been possible to gate the terahertz response to enable visualization of the reflections of the foam-air interface, when the reflection of the foam-air interface has significant temporal separation from the air-substrate interface. Figure 6 shows maximum amplitude of the signal before the beginning of the major reflection from the metal substrate. Two intentionally inserted disbonds are clearly visible in the images. In addition to the disbonds, outlines of voids are also visible in the image.

V. Detection of Voids in the Foam

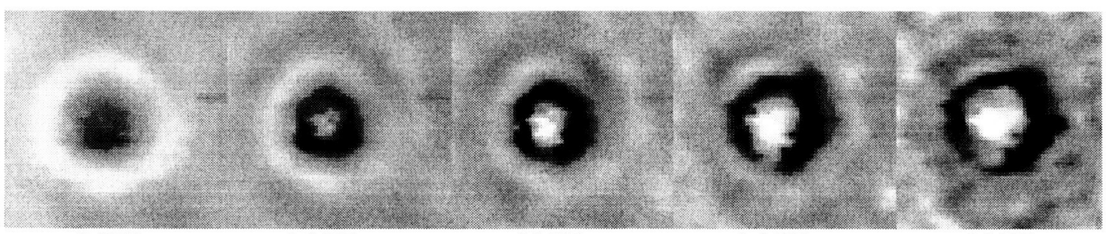
A second flaw terahertz has been successful in detecting is voids in the foam. The void consists of a large pocket of air trapped in foam, where large is defined as being significantly larger than the typical pore size of the foam. The electromagnetic phase velocity is slightly faster in the air than in the foam, therefore waves propagating in the foam are retarded in time relative to a wave propagating in the void. The two waves interfere with each other if they simultaneously arrive at the detector. The amount of interference depends on the amplitudes of the two waves and the relative phases of the two waves, which in frequency dependent. The relative phases of the two waves, assuming one travels through the void twice, is

$$\Delta\phi = 2d(k_a - k_f) \qquad (3),$$

where d is the length of the path in the void, k_a is the wave number in the air and k_f is the wave number in the foam. The amount of destructive interference increases with frequency until the two waves are 180 degrees out of phase with each other. At that point, as the frequency increases, the waves become more in phase with each other. For an index of refraction of 1.02, for a path differential of 2.5 cm (a void width of 1.25 if the wave passes through the void twice) the smallest frequency for the maximum interference is approximately 0.3 THz.

A second contrast mechanism is the difference in the attenuation between the air and the foam. The attenuation as can be seen in figure 2 is very frequency dependent. As a point reference, the attenuation for the foam at 0.2 THz is 4 times less than the attenuation at 0.4 THz. For differential path 2.5 cm, there is a 12% difference in amplitudes as a result of attenuation in the foam at 0.2 THz and 40% at 0.4 THz.

The combined effects of these two contrast mechanisms for a cylindrical hole, 1.25 cm tall and a 2.5 cm in diameter are shown in figure 7. The images represent the amplitude of the responses at a series of different frequencies as determined from the Morlet transform of the terahertz signal. The amplitude of each of the images has been normalized by dividing the values in the image by the average amplitude of signals away from the void. All of the images have then been scaled to the same minimum and maximum. The progression of images from low to high

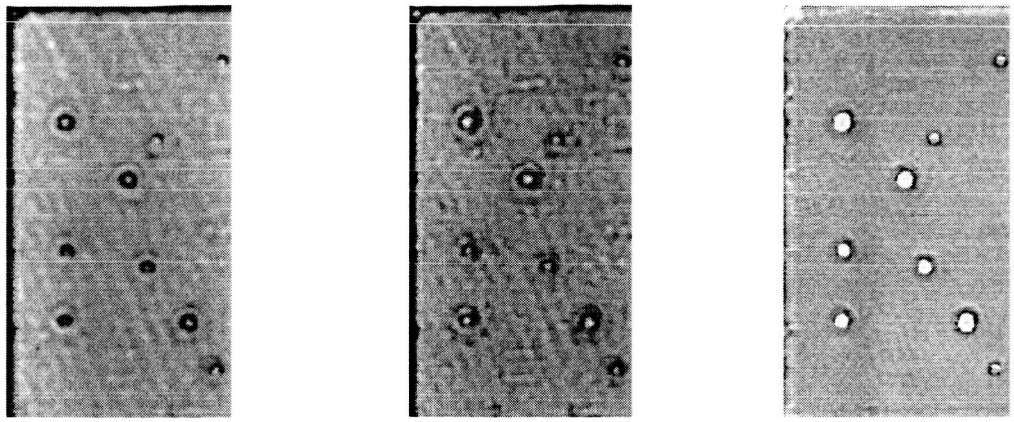


0.1THz 0.2 THz 0.3 THz 0.4 THz 0.5 THz

Figure 7. Responses of 2.5 diameter cylinder void in foam 1.25 cm tall as function of frequency.

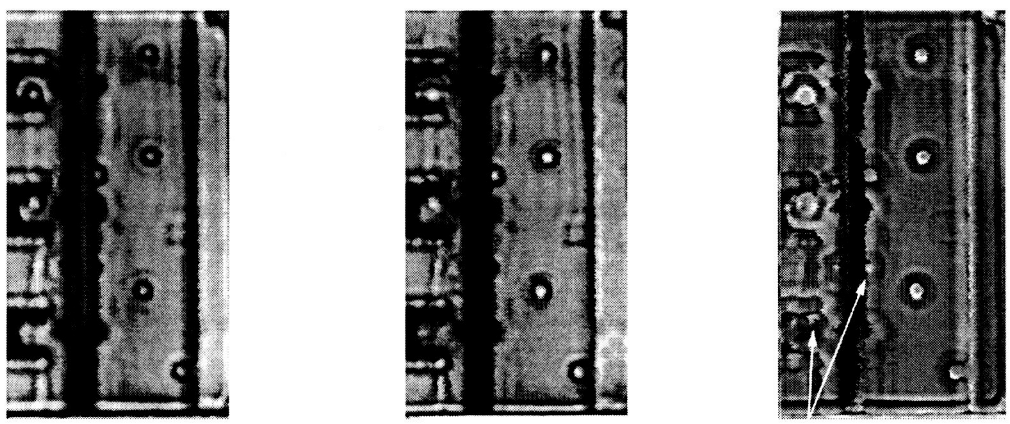
frequency shows the trends expected in the void response. A decrease in the signal appears at the edge of the void as a result of the destructive interference between the wave passing through the air and the wave passing through the foam. The decrease in signal level becomes greater as the frequency increases. The large difference in attenuation between the foam and the air at higher frequencies results in a higher amplitude in the signal at higher frequencies for waves with a path through the void. This is most notable at the center of the void, where the effect from inference is less significant.

Enhancing the visualization of voids is possible by developing a processing technique that accentuates the frequency dependence of the contrast mechanisms. One technique that significantly improves the contrast between voids and the foam is a difference between the log of an amplitude image at a higher frequency and a linear fit of the log of same image with the independent variable being the log of an image of the same area of the specimen at a lower



Amplitude of unfiltered response | Amplitude of response after 0.5 THZ band pass filter | Fit difference image

Figure 8. Images of generated from terahertz response from foam layer with cylindrical voids.



Amplitude of unfiltered response | Amplitude of response after 0.3 THZ band pass filter | Fit difference image

Figure 9. Images of generated from terahertz response from foam on substrate similar to the external tank. *Arrows indicate voids that are visible in the fit difference images, at are not visible in the filtered or unfiltered images.*

frequency. The fit accentuates similar features in the two images, such as variations in geometry. The fit difference accentuates features that change significantly with frequency such as the voids.

The improvement in contrast between voids and the surrounding foam as a result of this processing can be seen in figures 8 and 9. Figure 7 is of a flat foam panel with multiple cylindrical voids with diameters ranging from 0.6 to 2.5 cm in diameter and 1.2 cm in height. The comparison images are the amplitude of an unfiltered response and a high frequency band pass filtered response shown in the same figure as the fit difference image. As can be seen in a visual comparison of the images, the fit difference image increases the contrast between the void response and the normal variations in foam response. For the fit difference image, the signals from all of the voids are clearly greater than the background noise.

In figure 9, results are shown for a specimen with a substrate more characteristic of the external tank. In the unfiltered amplitude image, structures in the substrate such as the stringers, give variations in amplitude that are as significant as the voids. In the fit difference image, the voids become the dominant feature. The variations in the image due to substrate structure, while still visible, are significantly muted. Two voids that are not distinguishable in the unfiltered and filtered images become visible in the fit difference image.

VI. Conclusion

The pulse terahertz has been shown to be a very successful technique for the detection of air filled voids and delaminations in sprayed on foam insulation characteristic of the foam insulation used on the shuttle external tank. The mechanisms that result in the contrast between these air filled flaws and the unflawed foam are frequency dependent. It has been shown that it is possible to use this frequency dependence to enhance the contrast between the flaws and unflawed material. Further work is proceeding to determine the detection limits of the technique for varying configurations of the foam and metal substrate.

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